The Feasibility of Missile Launch Detection Through Clouds Using the 589.6 nm Na Emission

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ABSTRACT

Spectral measurements of various solid- and liquid-propellent rocket plumes have shown the presence of strong emissions from sodium (589.6 nm) and potassium (766.5 nm). Theoretical calculations indicate that emissions near 589.6 nm should be efficiently transmitted through the atmosphere and clouds and thus should be easily detectable by a downward-looking sensor positioned above the clouds. To test this concept, a visible radiometric sensor with an interference filter (and later with an atomic line resonance filter) was developed and flown on an aircraft platform. A simple ground-based Na emission source was fabricated using several low-pressure sodium discharge lamps. A number of nighttime measurement flights were conducted for several different cloud types and conditions. Data collected during these nighttime flights are presented and discussed. These initial measurements have confirmed that a simulated rocket emission source at 589.6 nm is detectable through clouds. Additional measurements covering a wider range of cloud conditions and types and during daylight conditions are planned for the near future.

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1.0 INTRODUCTION

Prominent atomic emission features from sodium (Na) and potassium (K) have been observed with ground-based optical sensors in the first-stage plumes of both solid - and liquid-fuel rockets.[1,2] Strong Na and K features have also been seen in the second-stage plume as well as during the period following first-stage burn-out and before second-stage ignition. A prominent Na feature was also observed through heavy rain from a first-stage plume by a sensor at a range of 1.6 km. [3] As a result of these observations and theoretical calculations of multiple scattering through clouds, we established a measurement program to determine the extent to which the Na emission is transmitted through various types and thickness of clouds and whether it can be detected during daylight in the presence of sunlight scattered from cloud tops. This paper describes the preliminary results of this measurement program.

2.0 INSTRUMENTATION DESCRIPTION

A visible photometer for airborne operation was fabricated and tested in the laboratory. This sensor consisted of a narrow-band filtered photometer, a lock-in amplifier, a radio receiver to receive a reference signal, data acquisition electronics, and a notebook computer to monitor and record the data.

The photometer had a 50 mm-diameter collecting aperture and a full-angle field of view of 2.0 degrees. A Hamamatsu photomultiplier (model H6180-01) was used as the detector. A 10-nm-wide interference filter centered at 590 nm was used to pass sodium emissions and to reject the background. Typically, the sensor was flown at an altitude that was 2000 feet above the cloud tops. At this range the photometer footprint at the cloud tops was about 21 meters.

The lock-in amplifier was manufactured by Stanford Laboratories (model SR510) and was configured to synchronously rectify the signal from the photometer at twice the 50 Hz reference signal frequency. The analog output of the amplifier was fed to data acquisition electronics where digital samples were taken at a rate of 10 times per second. The sampled digital data was recorded on the hard drive of a Toshiba notebook computer. The notebook computer also provided a real-time display of the photometer output.

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1. Selby, J. E., Cox, J. W., and Patterson, N., "Spectral Analysis of Low Altitude Theatre-class Missile Signatures" (U), IRIS Targets, Backgrounds and Discrimination, Monterey, CA, Feb. 1994.

2. Laufer, P. M., Scott, M. G., and Oliver, S. M., "Assessment of Predictive Capability for IR Signatures of Solid-Fueled TBM Threat Systems" (U), IRIS Targets, Backgrounds and Discrimination, Monterey, CA, Feb. 1994.

3. Oliver, S. M., Scott, M. G., Moyers, R. L., Bratcher, T. W., and Laufer, P. M., "Ground-Based VIS/IR Radiometric Measurements on Two U. S. Surrogate Solid-Propellant Theatre Ballistic Missiles (TBM)" (U), IRIS Targets, Backgrounds and Discrimination, Monterey, CA, Feb. 1994.

Ground sources were fabricated using a number of 180 Watt low-pressure sodium discharge lamps. Each bulb is approximately 1 meter long and is rated at 33,000 lumens. These bulbs were assembled in pairs with a common reflector element to create 360 W lamps. These lamps were then arranged on the ground at Hanscom AFB in a pattern resembling the spokes of a wheel to create a source with an effective circular diameter of approximately 2 meters. For the initial measurements at night, three lamps were arranged in a Y-shaped pattern. This created a modulated output of approximately 26 W/sr. For the daytime measurements, two additional lamps were added, for a total of 10 bulbs in all. However, due to limitations of the power generator only 9 of these bulbs were actually operated.

3.0 EXPERIMENT DESCRIPTION

An aircraft measurement program was initiated by AFRL to measure the diffuse transmission of clouds and to determine the spatial distribution of the scattered radiation at the top of the clouds. The experiment consisted of viewing the cloud tops with an airborne sensor while the clouds were being illuminated from below by a modulated ground-based sodium emission source. The basic experimental concept is illustrated in Figure 1. Since our simulated rocket source put out only a small fraction of the energy emitted by an actual rocket plume, we employed a synchronous AC sensor to effectively reject the background so that the source signal could be more easily detected. In order to discriminate against other modulated sources of sodium emission from sodium street lamps, etc. the "target" source was powered by a 50 Hz generator rather than the standard 60 Hz line power. This resulted in a source emission modulated at 100 Hz, whereas other modulated sources of Na emission from street lamps were modulated at 120 Hz. A 50 Hz reference signal derived from the 50 Hz generator was transmitted to the airborne sensor. A vertical pointing TPQ 11 35 GHz (0.86 cm) radar, located near the Na light source at Hanscom AFB, was used to measure cloud top and bottom altitudes.

The photometer was mounted in the baggage compartment of a twin-engine Beechcraft Duchess aircraft. The photometer looked out through a window and periscope, which were mounted in the baggage compartment door. The periscope contained a mirror at 45° and could be rotated to allow the photometer to view the cloud tops at any desired nadir angle. Most of the data was taken at a nadir angle of zero degrees, but a few measurements were conducted with nadir angles up to 60°. A GPS receiver onboard the aircraft recorded the position of the aircraft as a function of time.

In order to minimize the photon background level, the initial measurements were conducted at night. After these initial nighttime measurements had been successfully completed, the sensor was modified for daytime operation by replacing the 10-nm-wide interference filter with a much narrower (~ 0.005 nm) atomic line filter (ALF). The atomic line filter (also called a "Faraday atomic line filter" or simply just a "Faraday filter") was obtained from AstroTerra Corp, San Diego, CA. The filter incorporates a heated sodium vapor cell with a magnetic field between two crossed polarizers. The crossed polarizers block the background radiation while the signal polarization is rotated by 90°, thus allowing it to pass through the filter. Polarization rotation in the magnetic field is due to the Zeeman effect, which causes a separation in the optical absorption frequencies for right- and left- circularly polarized light. The passband frequency and bandwidth are dependent on temperature and magnetic field and can be adjusted over a relatively wide range. This filter is used in conjunction with a narrow band (0.5 nm) interference filter to help reject background radiation in the far wings. Unfortunately, our ALF has been plagued by vapor cell degradation due to sodium depletion and birefringent effects in the cell windows that have combined to degrade the filter performance. A replacement ALF has performed substantially better. However, these initial difficulties have resulted in several delays in the original measurement schedule.

4.0 DATA SUMMARY

Several aircraft data collection flights were conducted over Hanscom AFB, MA in the fall of 1997. These data flights were flown at night for two distinctly different "cloud" conditions. The first of these flights was conducted on September 4, 1997. This flight measured the transmission of the sodium ground source through a 1000 foot-thick stratus cloud located between 6000 - 7000 ft in altitude. Figure 2 shows the signal intensity measured through this cloud as a function of horizontal distance. The measured peak radiance was 4.5 x 10^{-10} W/cm^{2}sr and the spatial extent was approximately 3.9 km (between the 5% points). During another flight on October 10, 1997, with the aircraft flying at 10,000 feet, the sensor observed the ground source through a much thicker but less dense fog "cloud". This fog layer extended from approximately 1000 to 8000 ft. in altitude and was of a type generally referred to as "radiation fog". This type of fog is characterized by relatively small-diameter droplets (< 2 μm). The measured intensity through this fog layer versus horizontal distance in kilometers is shown in Figure 3. The peak brightness was 2.3 x 10^{-9} W/cm^{2}sr and was measured directly over the target. The spatial extent of the diffused source at the top of the layer was approximately 1.5 km, again measured between the 5% points. The noise equivalent (background) radiance (NER) for these measurements was ~ 1.0 x 10^{-12} W/cm^{2}sr, thus yielding S/N ratios in excess of 450.

In both of the above cases, the clouds were visibly opaque. Each of these cloud types was modeled using a Monte Carlo code in order to estimate the extinction coefficients. Based on these simulations, extinction coefficients are estimated to be approximately 9 and 48 km^{-1} for the radiation fog and stratus cloud, respectively. Using these estimates for the extinction coefficients, we have estimated the Liquid Water Content (W) for both cases using the empirical relationships given by Brown and Kunkel, 1985. [4] These estimated values are W = 0.02 - 0.06 g/m^3 and 0.3 - 0.4 g/m^3 for the fog and stratus cloud, respectively.

5.0 RADIATIVE TRANSFER CALCULATIONS

To predict the conditions under which detection of rocket plumes through clouds is feasible, we have employed a Monte Carlo radiative transfer code. The code solves the multi-frequency continuum (absorption and scattering) three-dimensional radiative transfer problem for externally (bottom and/or top) illuminated clouds, composed of any combination of ice crystals, water droplets, and dust particles of any size. We are currently modeling liquid water clouds of a known type, from which we estimate the droplet size distribution in the cloud. Scattering and absorption cross-sections and the scattering phase function are calculated according to Mie theory (based on the codes of Bohren & Huffman, 1983 [5]), using optical constants for water from Segelstein, 1981. [6]

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4. Brown, H. A. and Kunkel, B. A., "Handbook of Geophysics and the Space Environment" (U), Air Force Geophysics Laboratory (AFGL), p. 16-54, 1985.

5. Bohren, C. F. and Huffman, D. R., "Absorption and Scattering of Light by Small Particles.", Wiley, New York, 1983.

6. Segelstein, D., "The Complex Refractive Index of Water.", M. S. Thesis, U. of Missouri, Kansas City, 1981.

The code has been validated against proven one-dimensional models and three-dimensional analytic cases.

Using the above model, and cloud thickness parameters as measured for the experiments, we have successfully modeled the two nighttime observations of sodium lamp emission through clouds. In both cases, the derived opacity of the clouds determined from the model was consistent with the expected opacity range for the cloud type. We have compared these models directly to measurements of low pressure sodium lights measured through clouds, the results of which are shown in Figures 4 and 5. The first simulation is for a 0.3 km thick (altitude) "square" stratus cloud with horizontal dimensions of 4 km on a side and with a total optical depth of ~15. The second simulated "cloud" is a 2.1 km thick radiation fog with an optical depth of approximately 18 and horizontal dimensions of 6 km x 6 km. Due to the preferential forward-scattering of visible light by water droplets, the source spot remains fairly localized as it scatters up through the cloud. As a result, even at relatively high opacities, the location of the source on the ground can be readily determined from these observations.

For daytime detection of rocket plumes through clouds, the radiation spot at the cloud top from the source must be observable in the presence of the background signal due to backscattered radiation from the sun. We have attempted to simulate the experimental conditions of a nominal daytime measurement by modeling the scattered solar radiation from the tops for the two cloud types modeled above. To accomplish this, we assumed a geometry in which solar radiation was incident at 45 degrees to the cloud tops and we calculated the percent of the incident radiation scattered into the zenith angle. We found that only about 0.5% of the total solar radiation will be scattered into the zenith. Taking into account a factor of 20 attenuation due to the Fraunhofer absorption line, we expect the solar irradiance in the Na line to be 0.0065 W cm^{-2} μm^{-1}. Using an atomic line filter with a band pass of 0.005 nm, we find that the reflected solar radiance is about 1.4×10^{-9} and 4.1×10^{-10} W cm^{-2} sr^{-1} for the stratus cloud and fog layer, respectively. These background radiance values are shown as the dashed lines in Figures 4 and 5, respectively. For comparison, the cloud model simulations for the two nighttime cases are also shown (as the solid curves) in Figures 4 and 5. By adding the modeled scattered sunlight to the nighttime simulations for each case, we have simulated two "typical" cloudy daytime scenarios. These are shown by the dotted curves in Figures 4 and 5 respectively. As seen in Figure 4, the peak radiance of the source seen through the stratus cloud is about a factor of three less than the predicted backscattered solar radiance for this cloud. Under these conditions, the source emission might easily be obscured by the natural variations in the cloud background. The situation is essentially reversed for the much less dense fog layer represented in figure 5. Here the source signal is expected to exceed the background and thus should be observable during the day. Based on these initial results, it appears that the signal from the sodium ground source could be detectable with a DC-coupled system under certain minimally-cloudy conditions in the daytime as long as the peak radiance of the source through the clouds is comparable to the natural variations in the radiance observed from the cloud top.

Due to our synchronous AC detection scheme, which effectively eliminates unmodulated background signals, we expect to have little more difficulty detecting the modulated sodium ground source during the day than was encountered at night. Although background photon levels will be orders of magnitude higher than at night this will be at least partially compensated for by the use of the much narrower (~2000X) atomic line filter. Overall, the photon noise level for the daytime measurements is expected to increase by about an order of magnitude. However, these initial daytime experiments will provide little information concerning the ability of space-based sensors to detect rockets during the daytime. They are being conducted primarily to evaluate the operation of the ALF in preparation for subsequent cloud background characterization flights using a DC-coupled sensor.

6.0 FUTURE PLANS AND ACTIVITIES

Future plans include upgrading the measurement platform to one which will allow considerably more flexibility of operation. The single most important deficiency encountered in this measurement program, to date, has been flight cancellations caused by operational limitations of the twin-engine Beechcraft aircraft. This airplane is not equipped with a de-icing system and has an operational ceiling of only 12,500 feet. These factors have combined to cause the cancellation of numerous potential data flights. Most often, cloud tops were simply above the aircraft's operational ceiling. At other times, aircraft icing or high cross winds resulted in cancellations. Overall, these limitations and constraints resulted in many missed opportunities to collect data during cloudy daytime conditions.

Operational difficulties aside, the near-term objectives of the program are to measure the intensity and spatial distribution of the Na ground source radiation which penetrates various types and thicknesses of clouds and fogs. This includes measurements for both nighttime and daytime conditions. The primary objective of the daytime measurements will be to characterize the natural variations in the solar backscattered background radiance for various cloud types, cloud top altitudes and solar illumination conditions. Naturally, these measurements will need to be performed using a DC-coupled system. Longer term objectives include measurements for both rain and snowstorm conditions.

In order to achieve these objectives, a number of source, sensor and/or filter upgrades are planned for near-term implementation. In addition, several alternate sensors are also being considered for future measurements as a part of our ongoing program. One of these measurement alternatives is a high-throughput visible Fabry-Pérot sensor, which is being developed under a separate program. This sensor (which is being planned for installation on a high-altitude aircraft) will be operated in multiple orders to provide a wide field of view in addition to its inherently high spectral resolution. This instrument will allow us to characterize and exploit the high resolution spectral differences between the actual rocket plume signatures and other sodium emission sources, such as high- and low-pressure sodium street lamps.

7.0 SUMMARY AND CONCLUSIONS

Various ground-based plume measurements have suggested that early time launch detection might be feasible with space-based or airborne sensors operating in a narrow band at 590 nm. In addition, scattering calculations have indicated that detection of missile launches at this wavelength should also be possible during cloudy or overcast conditions. These calculations predict that sufficient radiation from the rocket plume will be forward scattered up through clouds, and that this diffused radiation will be sufficiently localized to be detectable by an overhead sensor. Due to the relatively small size of the radiation pattern at the top of the cloud, this technique also holds the promise of providing accurate information on the launch site location. Furthermore, operating in a very narrow spectral band also substantially reduces the background emissions seen by such a sensor. By operating in the Fraunhaufer absorption region at 590 nm, the solar background can be even further reduced, thus allowing the real possibility that such a sensor could successfully operate for both nighttime and daytime conditions. Initial nighttime measurements for two different cloud conditions have provided a quantitative measure of the intensity and spatial spread of a Na source at the top of clouds. However, additional observations covering a much wider range of cloud types and thicknesses still need to be conducted. Daytime measurements of cloud backgrounds are also necessary in order to accurately assess the potential operational utility of this technique during the daytime. While daylight measurements to date have been hampered by instrumentation problems associated with the atomic line filter and by operational constraints imposed by the small aircraft presently being utilized, we anticipate that initial daytime measurements will be conducted in the near future.

8.0 ACKNOWLEDGEMENTS

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Segelstein, D., "The Complex Refractive Index of Water.", M. S. Thesis, U. of Missouri, Kansas City, 1981.

Figure Captions

Figure 1. An artist's depiction of the experimental configuration.

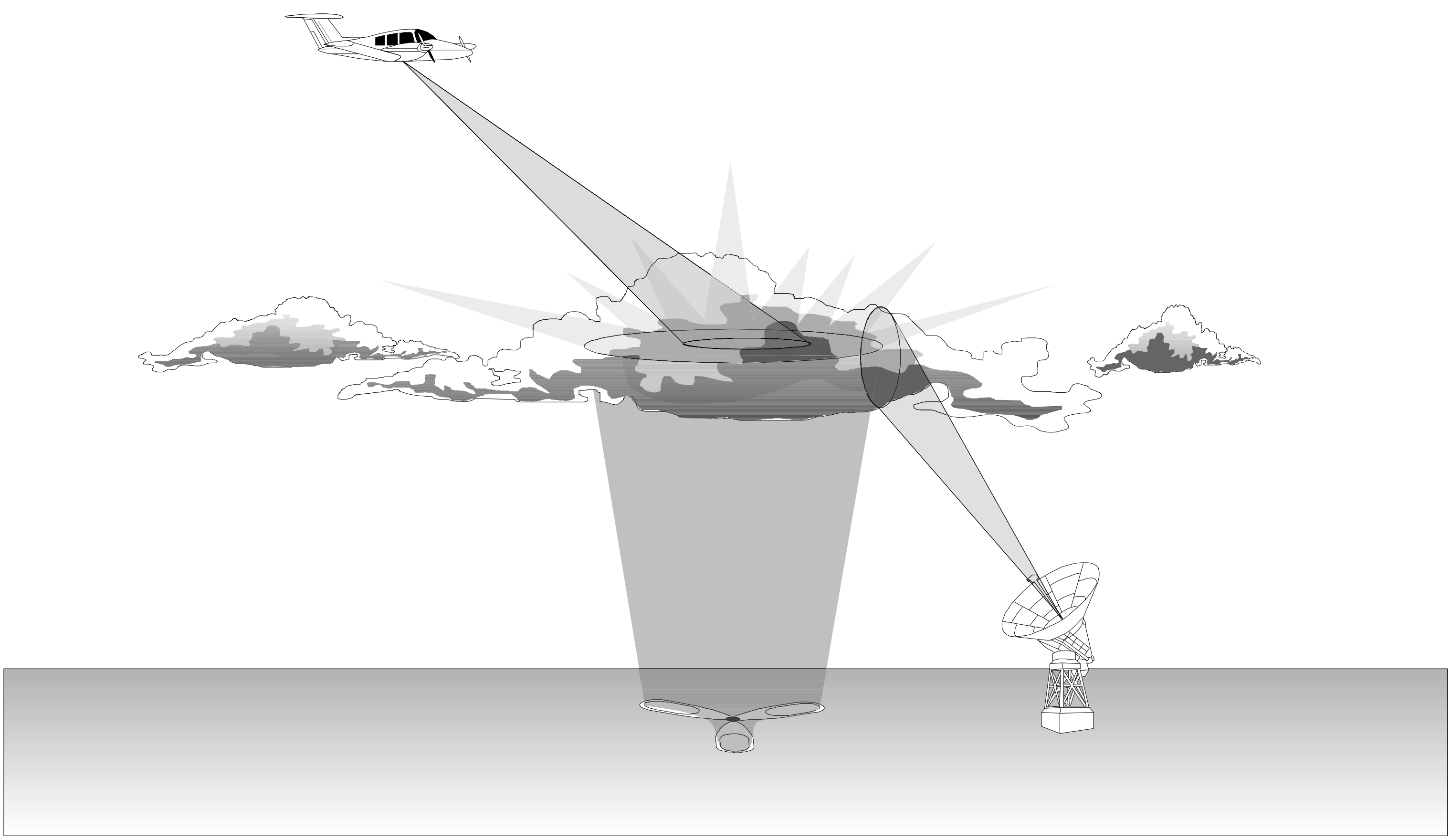
Figure 2. Measured intensity of the low-pressure sodium ground source as observed through a 0.3 km-thick stratus cloud as a function of horizontal distance in kilometers.

Figure 3. Measured intensity of the low-pressure sodium ground source as observed through a 2.1 km-thick radiation fog layer as a function of horizontal distance in kilometers.

Figure 4. Three-dimensional transfer model of a low-pressure sodium source seen through a 0.3 km-thick stratus cloud (solid curve). The peak radiance has been normalized to the experimentally observed value. The expected backscattered solar radiance is shown by the dashed line and is described in the text. Variations on the order of 30% have been introduced into the model to approximate the natural cloud top variations. The dotted curve represents the model prediction of the sodium source as seen through the cloud during the daytime.

Figure 5. Three-dimensional transfer model of a low-pressure sodium source seen through a 2.1 km-thick radiation fog (solid curve). The peak radiance has been normalized to the experimentally observed value. The expected backscattered solar radiance is shown by the dashed line and is described in the text. Variations on the order of 30% have been introduced into the model to approximate the natural cloud top variations. The dotted curve represents the model prediction of the sodium source as seen through the fog during the daytime.

FIG 1.



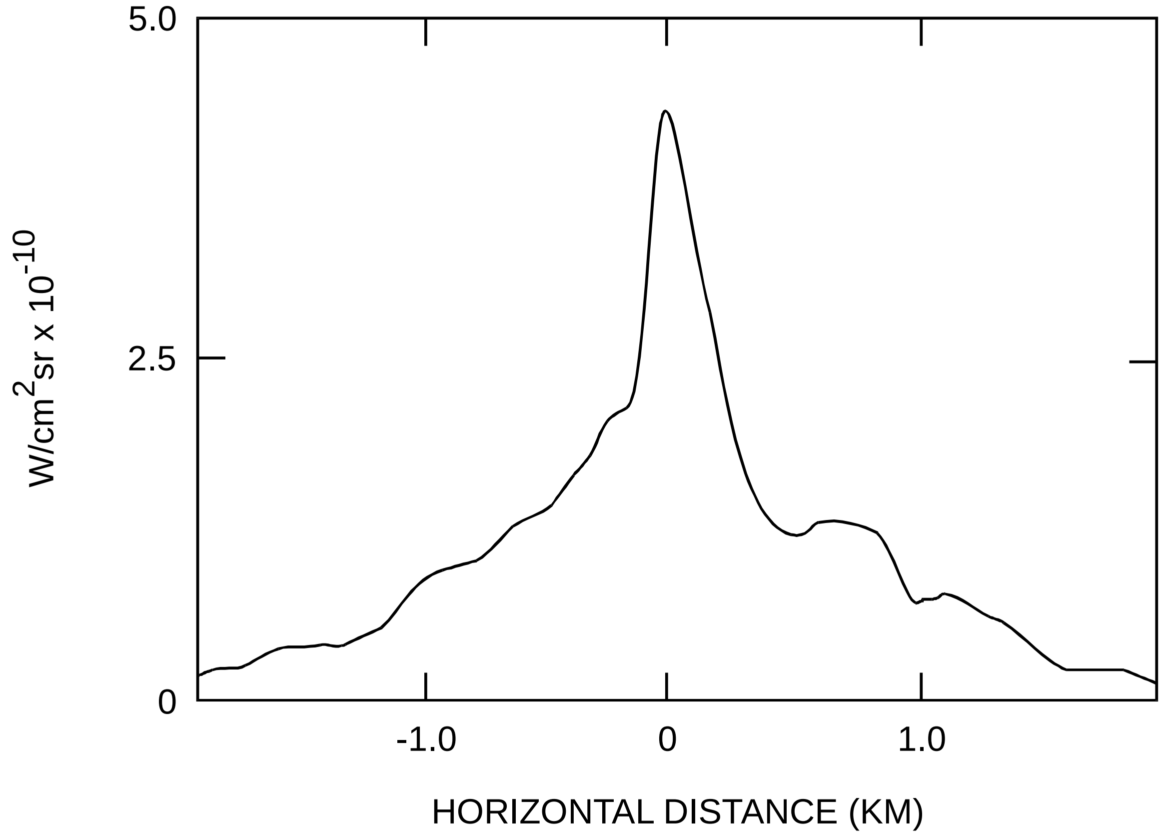


FIG. 2

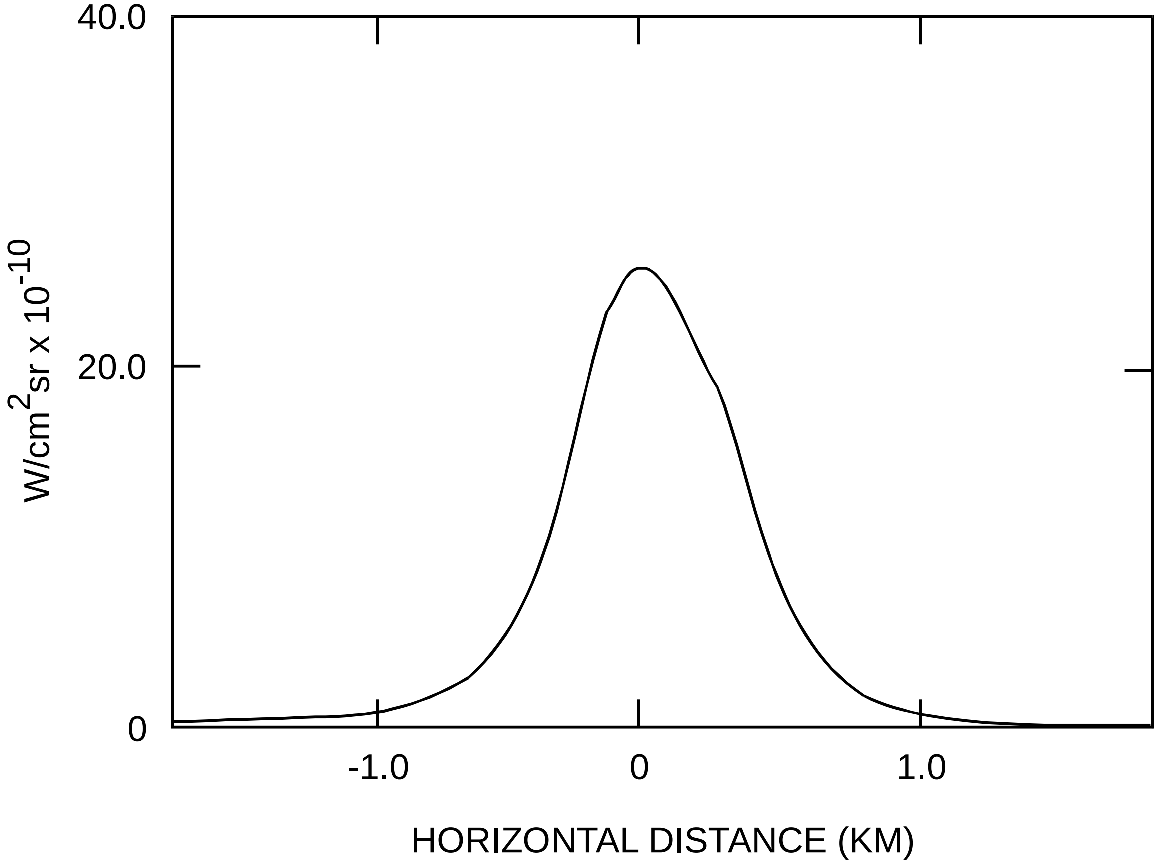


FIG 3.

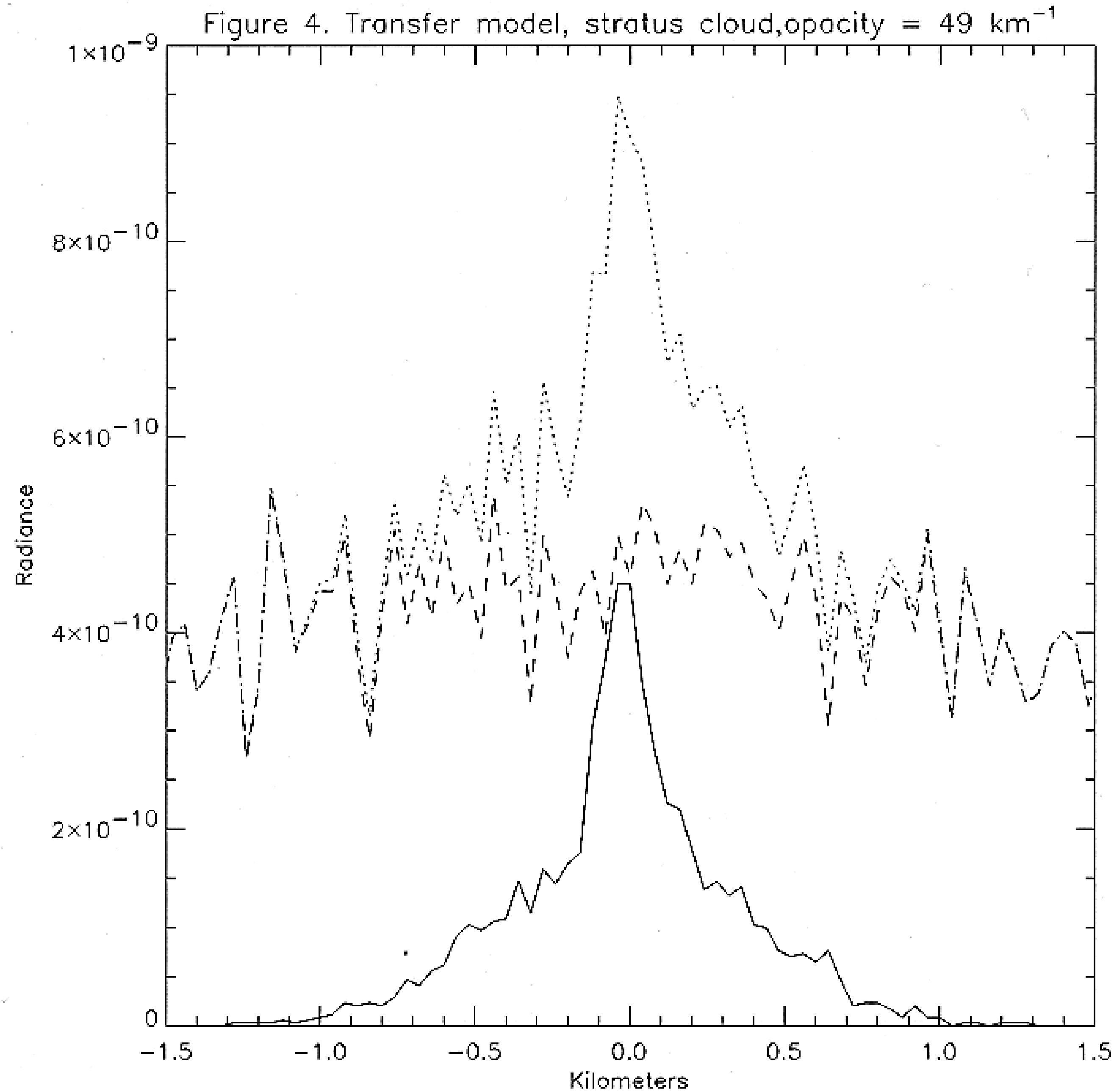


Figure 4. Transfer model, stratus cloud,opacity = 49 km^{-1}
Radiance
Kilometers
1×10^{-9}
8×10^{-10}
6×10^{-10}
4×10^{-10}
2×10^{-10}
0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5

FIG 4.

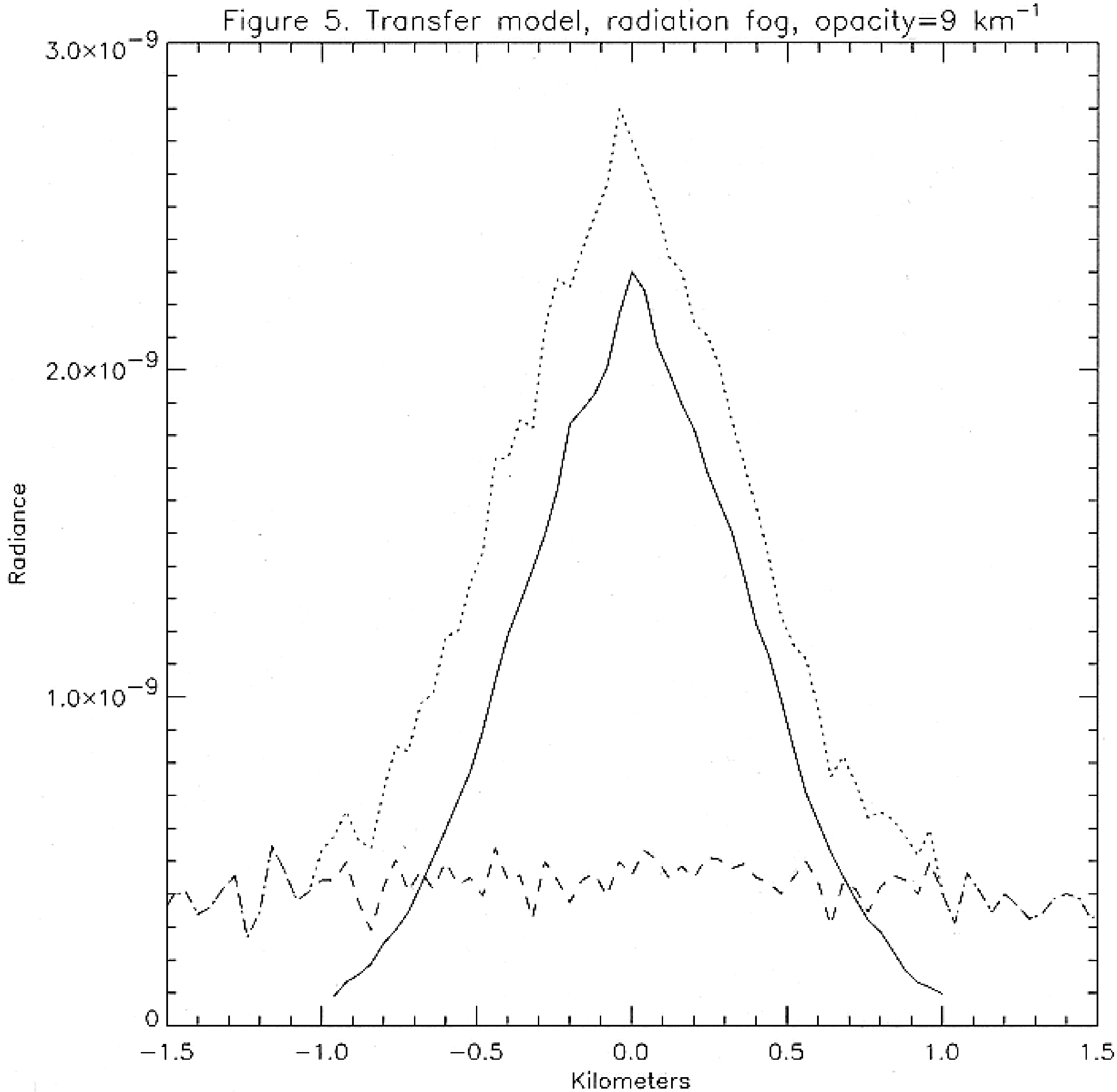


Figure 5. Transfer model, radiation fog, opacity=9 km^{-1}
3.0×10^{-9}
2.0×10^{-9}
1.0×10^{-9}
0
Radiance
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
Kilometers

FIG 5.